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Fast encoding/decoding of haptic microneurography data based on first spike latencies

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During haptic exploration tasks, forces are applied to the fingertips, which constitute the most sensitive parts of the hand and are prominently involved in object manipulation/recognition tasks. The epidermis is innervated with thousands of sensory cells, called mechanoreceptors, that encode the mechanical indentations and deformations of the skin. These cells project directly to a dorsal column nucleus called the cuneate nucleus (CN) that constitutes the first synaptic relay to the central nervous system. Recent microneurography studies in humans [1] suggest that the relative timing of impulses from ensembles of mechanoreceptor afferents can convey information about important contact parameters faster than the fastest possible rate code and are fast enough to account for the use of tactile signals in natural manipulation.

Here, we study a biologically plausible encoding/decoding process accounting for the relative spike timing of the signals propagating from peripheral nerve fibres onto second-order CN neurons. The CN is modelled as a population of 450 spiking neurons receiving as inputs the spatiotemporal responses of real mechanoreceptors obtained via microneurography recordings in humans. An information-theoretic approach is used to quantify the efficiency of the haptic discrimination process. To this extent, a novel entropy definition has been derived analytically. This measure proved to be a promising decoding scheme to generalize the classical Shannon's entropy for spiking neural codes, and it allowed us to compute mutual information (MI) in the presence of a large output space (i.e., 450 CN spike train responses) with a 1 ms temporal precision. Using a plasticity rule designed to maximise information transfer explicitly [2], a complete discrimination of 81 distinct stimuli occurred already within 40 ms after the first afferent spike, whereas a partial discrimination (80% of the maximum MI) was possible as rapidly as 20 ms.

The rationale behind this study was to corroborate our working hypothesis that the CN does not constitute a mere synaptic relay, but it rather conveys an optimal contextual account (in terms of both fast and reliable information transfer) of peripheral tactile inputs to downstream structures (in particular to the thalamus and the cerebellum). Therefore, the CN may play a relevant role in the early processing of haptic information and it would constitute an important component of the haptic classification process (e.g., by facilitating fast discrimination of haptic contexts, minimising destructive interference over lifelong learning, and maximising memory capacity).

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